Year: 2019

Validation of a Virtual Reality-Based Hip Arthroscopy Simulator

Bauer, David E ; Wieser, Karl ; Aichmair, Alexander ; Zingg, Patrick O ; Dora, Claudio ; Rahm, Stefan

Abstract: PURPOSE To assess construct and face validity of a novel virtual reality-based hip arthroscopy simulator using the previously validated Arthroscopic Surgery Skills Evaluation Tool (ASSET), metric parameters, and a questionnaire. METHODS Metric parameters including task completion time, camera path, and grasper path were recorded, and the ASSET score was used to assess construct validity. Face validity was evaluated using a questionnaire. RESULTS Nine hip arthroscopy experts, of whom the majority performed more than 200 procedures (age, 48 ± 7.3; range, 38-61 years; 8 men, 1 woman), and 33 nonexperts (age, 33 ± 7.9; range, 26-62 years; 25 men, 8 women) performed 3 individual tasks on a virtual reality-based arthroscopy simulator of a left hip. The ASSET global rating scale showed a statistically significant difference between the hip arthroscopy expert and the nonexpert group, indicating strong construct validity (25.0 in the expert group, range, 17-34, versus 15.30 in the nonexpert group, range, 8-30 [$P < .001$], respectively). This also applied to most metric parameters recorded by the simulator. The simulator also demonstrated high face validity. The overall impression in terms of realism was graded "completely realistic" by 17% and "close to realistic" by 62% of participants. CONCLUSIONS The tested simulator demonstrated high construct and face validity. CLINICAL RELEVANCE This study demonstrates the construct and face validity of a novel hip arthroscopy simulator. The device proved to be an adequate model for the simulation of some arthroscopic procedures of the hip.

DOI: https://doi.org/10.1016/j.arthro.2018.10.131

Originally published at:
Bauer, David E; Wieser, Karl; Aichmair, Alexander; Zingg, Patrick O; Dora, Claudio; Rahm, Stefan (2019). Validation of a Virtual Reality-Based Hip Arthroscopy Simulator. Arthroscopy: The Journal of Arthroscopic Related Surgery, 35(3):789-795.
DOI: https://doi.org/10.1016/j.arthro.2018.10.131

Original Article With Video Illustration

Validation of a Virtual Reality–Based Hip Arthroscopy Simulator

David E. Bauer, M.D., Karl Wieser, M.D., Alexander Aichmair, M.D., M.P.H., Patrick O. Zingg, M.D., Claudio Dora, M.D., and Stefan Rahm, M.D.

Purpose: To assess construct and face validity of a novel virtual reality–based hip arthroscopy simulator using the previously validated Arthroscopic Surgery Skills Evaluation Tool (ASSET), metric parameters, and a questionnaire. **Methods:** Metric parameters including task completion time, camera path, and grasper path were recorded, and the ASSET score was used to assess construct validity. Face validity was evaluated using a questionnaire. **Results:** Nine hip arthroscopy experts, of whom the majority performed more than 200 procedures (age, 48 ± 7.3; range, 38-61 years; 8 men, 1 woman), and 33 nonexperts (age, 33 ± 7.9; range, 26-62 years; 25 men, 8 women) performed 3 individual tasks on a virtual reality–based arthroscopy simulator of a left hip. The ASSET global rating scale showed a statistically significant difference between the hip arthroscopy expert and the nonexpert group, indicating strong construct validity (25.0 in the expert group, range, 17-34, versus 15.30 in the nonexpert group, range, 8-30 [$P < .001$], respectively). This also applied to most metric parameters recorded by the simulator. The simulator also demonstrated high face validity. The overall impression in terms of realism was graded "completely realistic" by 17% and "close to realistic" by 62% of participants. **Conclusions:** The tested simulator demonstrated high construct and face validity. **Clinical Relevance:** This study demonstrates the construct and face validity of a novel hip arthroscopy simulator. The device proved to be an adequate model for the simulation of some arthroscopic procedures of the hip.

Since its emergence in the armamentarium of orthopedic surgeons in the late 1990s, the number of hip arthroscopies performed each year has increased tremendously.[1,2] It has been shown that acquiring the required skills to perform minimally invasive hip surgery safely and effectively remains a matter of extensive practice corresponding to a gradually ascending learning curve requiring extensive repetition of tasks to perfect the required skills.[3-7] Multiple studies evaluating the benefit of simulator-based training for hip-, knee-, and shoulder-related arthroscopic surgery were able to demonstrate that simulator-based training methods of arthroscopic skills facilitate steep learning curves corresponding to rapidly improving performance in the operating room.[6,8,9] A study assessing the performance of a dry model for arthroscopic acetabular labral repair demonstrated its validity and reliability as a training resource.[10] Another study showed that trainees with minimal experience in hip arthroscopy objectively improve their performance when using a dry model hip arthroscopy simulator.[11] However, dry model simulators are limited to only roughly represent anatomic structures and material properties. Furthermore, additional functionality including guided diagnostics, the simulation of different pathologies, and recording of metric parameters as a matter of objective performance feedback remain difficult. Virtual reality–based simulators provide the ability to sculpture these structures with high attention to detail and the possibility to alter physical properties of the arthroscopy environment and surfaces for instance by mimicking the movement of foreign bodies within fluid or elasticity of cartilaginous structures. The combination of highly detailed 3-dimensional anatomic models, realistic physical properties, and haptic feedback from the mock-up model provides a more realistic overall impression aiming at a high face validity

From the Department of Orthopaedics, Balgrist University Hospital, University of Zurich, Zurich, Switzerland.

The authors report that they have no conflicts of interest in the authorship and publication of this article. Full ICMJE author disclosure forms are available for this article online, as supplementary material.

Local ethics committee approval was obtained (BASEC-No. Req-2017-0475)

Received March 13, 2018; accepted October 27, 2018.

Address correspondence to David E. Bauer, M.D., Department of Orthopaedics, University Hospital Balgrist Zurich, Forchstrasse 340, 8008 Zurich, Switzerland. E-mail: dudi.bauer@gmail.com

0749-8063/18321/$36.00
https://doi.org/10.1016/j.arthro.2018.10.131

of the device. Accordingly, another virtual reality hip arthroscopy simulator providing haptic feedback via motors connected to the instruments already demonstrated its potential for developing basic arthroscopic skills.[12]

Furthermore, the metric parameters recorded by these devices can be used to assess performance and improvement of skills.[8] For this study, in addition to the recorded metric parameters, the previously validated Arthroscopic Surgery Skills Evaluation Tool (ASSET) has been applied to measure arthroscopy performance in this study. The ASSET score is a validated tool to evaluate the technical ability of surgeons performing arthroscopic surgery by grading seven arthroscopic skill domains from 1 to 5 (1 = novice to 5 = expert) and the autonomy of the performed procedure.[13]

The purpose of this study was to assess the construct and face validity of a virtual reality—based hip arthroscopy simulator. The authors hypothesized that the tested hip arthroscopy simulator will demonstrate high construct validity by being able to distinguish between participants with substantial experience in hip arthroscopy and nonexperts via metric parameters and the ASSET score and high face validity assessed via a questionnaire.

Fig 1. ArthroS hip arthroscopy simulator.

Methods

Orthopaedic residents and board-certified orthopaedic surgeons from different institutions were invited to perform 3 individual tasks on a prototype virtual reality—based hip arthroscopy simulator (ArthroS; VirtaMed AG, Schlieren, Switzerland). The device consists of a plastic replica of a left hip joint covered with rubber skin, with preset portals connected to a computer generating a virtual reality image of the arthroscopic anatomy of the hip joint. Tactile feedback results from collision between the instruments and the plastic replica of the hip joint within the rubber skin cover. An anterolateral, anterior, and posterolateral portal as described by Byrd et al.,[14] as well as a proximal mid-anterior portal as described by Dienst et al.,[15] placed in relation to palpable anatomic landmarks are provided to insert the instruments into the central and peripheral compartment of the hip joint (Fig 1). The instrument replicas correspond to standard surgical instruments connected via cables to the simulator.

A 2-minute standardized orientation phase to get acquainted with hardware and software was followed by 1 diagnostic task and 2 tasks requiring basic arthroscopic triangulation skills. During the orientation phase participants were guided through visualization of anatomic structures in the central compartment of the hip. The first task required visualization of the same anatomic structures of the central compartment without computer guidance. The anatomic structures required to be visualized in the central compartment were the acetabular fossa, the femoral head, the ligamentum teres, the anterior, posterior and superior acetabular cartilage, the anterior, superior, and posterior acetabular labrum, as well as the posterior and anterior transverse ligament.

For the second task participants were asked to remove 4 star-shaped foreign bodies from the central compartment of the hip using a grasper instrument. Finally, 5 foreign bodies placed from 11 to 7 o'clock position and at the lateral synovial fold needed to be removed from the peripheral compartment (Video 1). Access to the hip joint with the arthroscope and instruments was limited to the anterolateral portal for the first task and the anterolateral, as well as the anterior portal for the second task. For the third task participants were instructed to use the anterior portal for visualization and the anterolateral and distal anterolateral portal for the grasper instrument (Fig 2). Standardized hip extension and traction for tasks involving the central or 45° of hip flexion without traction for tasks involving the peripheral compartment were applied, respectively. The simulator was equipped with an arthroscope simulating 70° angled view. Task completion time in seconds, camera path, as well as grasper path in centimeters if applicable, were recorded. Video footage of the second task, requiring bimanual dexterity, orientation, and triangulation, was graded by

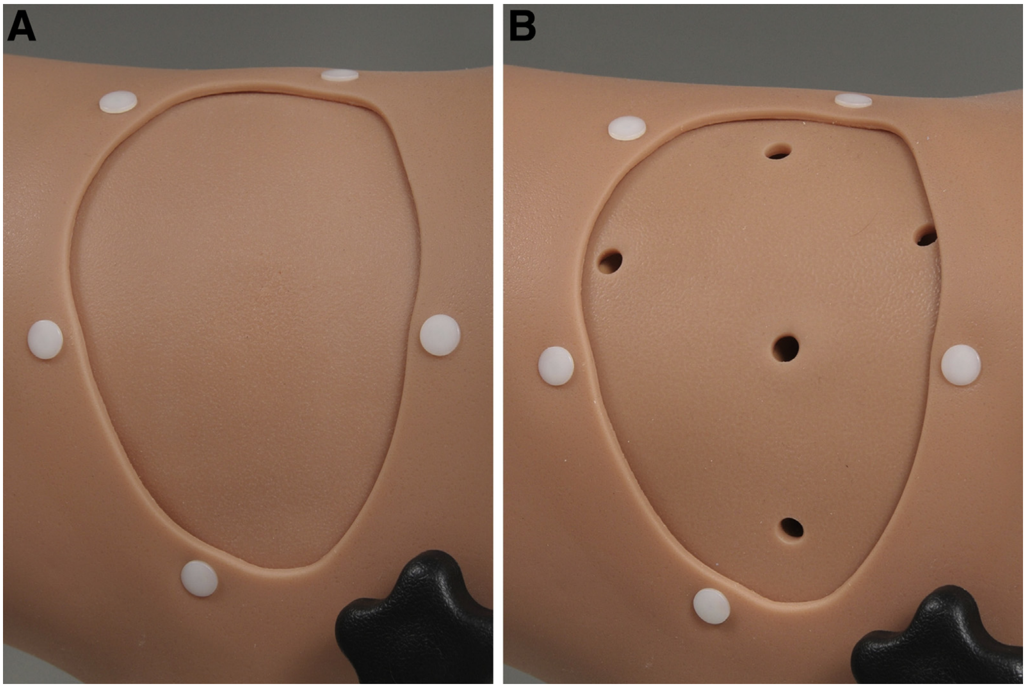

Fig 2. Mock-up model. (A) Memory foam inlay. (B) Inlay with preset portals.

2 independent, blinded, experienced arthroscopic surgeons using the validated ASSET.[13]

Nine surgeons experienced in hip arthroscopy were willing to participate in this study. Hip arthroscopy experts were also asked to establish an anterolateral portal to the hip joint. The portal was defined to coincide with the intersection of a sagittal line drawn distally from the anterior superior iliac spine and a transverse line across the superior margin of the greater trochanter. Therefore the area of mock-up model otherwise providing the preset portals was substituted with a penetrable memory-foam (Fig 2). The simulation device facilitates verification of correct placement of the probe by mimicking a fluoroscopic image.

Face validity of the mock-up model, the instruments, and the arthroscopic appearance of anatomic structures of the hip were evaluated by all participants using a 19-item questionnaire. The survey used a 7-point Likert scale with anchor statements (1 = not realistic to 7 = absolutely realistic and 1 = very useful to 7 = not useful at all) to evaluate realism and training utility in accordance to previously performed validating studies.

No funding was received for this project. Written, informed consent of participants and approval of the local ethics committee were obtained. This study was conducted according to the recommendations for reporting validation studies for surgical simulators.[16]

Statistical Analysis

Statistical analysis was performed with the Statistical Package for the Social Sciences version 21 (SPSS, Chicago, IL). Data are presented as mean and standard deviation for continuous variables and as proportion (%) for categorical variables, if not stated otherwise. The Kolmogorov-Smirnov test was used to test the distribution of metric parameters. Intraclass correlations were used to test for inter-rater reliability. The correlation between metric parameters and the ASSET was evaluated using the Pearson correlation coefficient. The Mann-Whitney-U test, Student *t* test, or χ^2 test was performed as applicable to test for differences between the novice and expert group.

Before studying construct validity, a power calculation for the null hypothesis ("performance of experts is equal to that of novices") with an acceptable significance (type 1 error, $\alpha = 0.05$) and acceptable type 2 error ($\beta = 0.20$, power = 0.8) was performed. We considered a 20% reduction in intervention time as a relevant difference. This resulted in a minimum number of 12 subjects in each group.

Results

Nine hip arthroscopy experts (mean age, 48 ± 7.3; range, 38-61 years; male, n = 8; female, n = 1) and 33 participants without prior experience in hip arthroscopy (mean age, 33 ± 7.9; range, 26-62 years; male, n = 25; female, n = 8) were included in this study. All but 1 participant in the expert group reported having performed more than 200 arthroscopic procedures of the hip. However, all experts performed more than 150 arthroscopic procedures of the hip. Participants not experienced in hip arthroscopy had varying levels of experience in arthroscopic procedures of the knee and/or shoulder, 12 board certified orthopedic surgeons or residents in their final year having performed at least 50 arthroscopic procedures of the knee and shoulder and 21 less experienced residents, respectively.

Construct Validity

The inter-rater reliability between the examiner ratings (R.S. and W.K.) for the total ASSET score was 0.96 (95% CI, 0.93-0.98). The ASSET global rating scale showed a statistically significant difference between the hip arthroscopy expert and the nonexpert group (25.0 $\pm$ 5.5; range, 17-34 vs 15.30 $\pm$ 6.0; range, 8 - 30; $P < .001$, respectively). Within the hip arthroscopy nonexpert group, there was no statistically significant difference in the total ASSET global rating scale between experienced shoulder or knee surgeons and novices to arthroscopic surgery ($P = .581$) (Fig 3).

The pairwise differences of the grasper path in task 3 were not significant. Otherwise, the remaining metric measures were able to distinguish between expert and nonexpert participants (Table 1). As opposed to the total ASSET, within the hip arthroscopy nonexpert group certain metric parameters showed a statistically significant difference between shoulder and knee surgeons with previous experience in arthroscopic shoulder or knee surgery and novices to arthroscopic surgery (Table 2). The total ASSET global rating scale significantly correlated with the task completion time ($r = -0.743$), the camera path ($r = -0.666$), and the grasper path ($r = -0.588$), respectively ($P < .001$).

Face Validity

Most participants graded the device itself, the virtual anatomic model, and the instruments to be either "completely" (7) or "close to realistic" (6). The overall impression in terms of realism was graded "completely realistic" by 17% and "close to realistic" by 62% of participants. However, passive haptic features of the bone and soft tissue were generally graded as less favorable ("completely realistic" and "close to realistic," 5% and 21%, respectively). The same applies for the mock-up model of the hip itself ("completely realistic" and "close to realistic," 14% and 38%, respectively). There was no significant difference in grading of face validity between the expert and the nonexpert group. A comprehensive synopsis of the results of the questionnaire assessing realism grouped by expert level is offered in Figure 3. Placement of the anterolateral portal was graded as "useful" (6) by 5, "somewhat useful" (5) by 3, and "less useful" (3) by 1 expert participant. Considering training utility, the simulator was thought to be a "very useful" (7) or "useful" (6) training device by both groups (33% and 55%, respectively) (Figs 4 and 5).

Discussion

The results of this study demonstrate that the simulator was able to distinguish between expert and nonexpert participants using metric parameters and the ASSET score and therefore demonstrated validity of the construct. Face validity of the simulator was supported by the results of the questionnaire.

By applying the ASSET score and measuring metric parameters, the simulator was able to distinguish between hip arthroscopy experts and nonexperts, thereby demonstrating strong construct validity.[17] Within the hip arthroscopy nonexpert group, this also applied to some of the previously validated metric parameters when comparing board-certified orthopedic surgeons and final-year residents with less experienced residents.[8,18] Furthermore, there was a significant

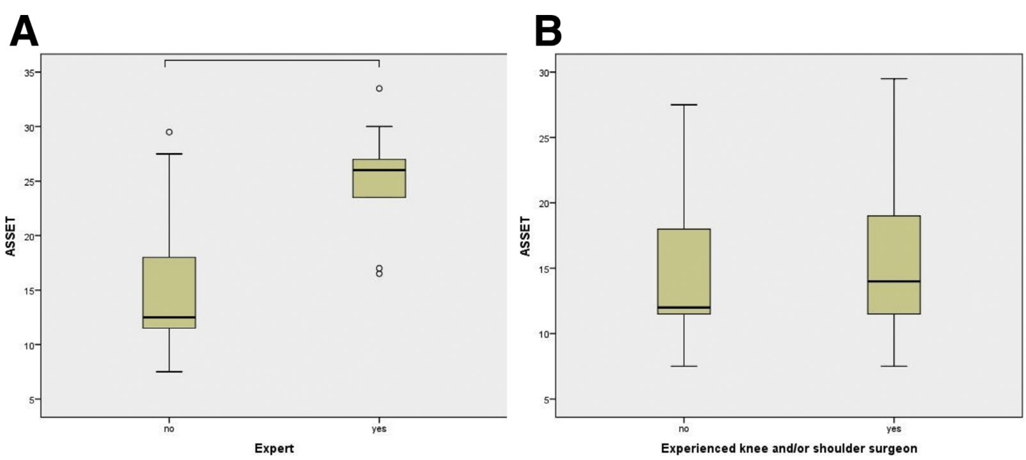

Fig 3. Summary of total ASSET global rating scale. Solid vertical black lines indicate medians, bottom of the boxes represent the 25th percentile, top of the boxes represent the 75th percentile, whiskers represent the range of the nonoutlier data, and circles represent the outliers between 1.5 and 3 times the interquartile range. Solid horizontal bar indicates statistically significant difference. (A) Experts vs nonexperts. (B) Shoulder and/or knee surgeons versus novices.

Table 1. Summary of Metric Parameters

	Nonexpert			Expert			P Values		
	Time (seconds)	Camera (cm)	Grasper (cm)	Time (sec)	Camera (cm)	Grasper (cm)	Time	Camera	Grasper
Task 1[*]	202.67 ± 64.85	141.20 ± 62.91	NA	99.89 ± 46.12	41.74 ± 15.05	NA	<.001[§]	<.001[§]	NA
Task 2[†]	242.33 ± 83.76	132.42 ± 52.93	238.70 ± 116.85	132.33 ± 50.35	59.73 ± 31.33	112.72 ± 58.90	.001[§]	<.001[§]	.003[§]
Task 3[‡]	266.27 ± 85.55	206.08 ± 113.51	141.71 ± 90.98	156.44 ± 55.36	83.40 ± 39.02	92.98 ± 46.80	.001[§]	<.001[§]	.13

NA, not applicable.
*Diagnostic central compartment.
†Foreign body removal central compartment.
‡Foreign body removal peripheral compartment.
§Statistically significant.

Table 2. Summary of Metric Parameters, Non–Hip Arthroscopy Experts

	Novice			Experienced Knee/Shoulder Surgeons			P Values		
	Time (seconds)	Camera (cm)	Grasper (cm)	Time (seconds)	Camera (cm)	Grasper (cm)	Time	Camera	Grasper
Task 1[*]	225.86 ± 59.63	168.67 ± 59.10	NA	162.08 ± 54.26	93.13 ± 34.64	NA	.014[§]	<.001[§]	NA
Task 2[†]	262.24 ± 81.86	148.48 ± 51.83	267.77 ± 124.32	207.50 ± 78.38	104.30 ± 43.71	187.84 ± 84.77	.104	.030[§]	.058
Task 3[‡]	280.24 ± 77.05	224.24 ± 101.62	142.34 ± 75.39	241.83 ± 97.33	174.31 ± 130.29	140.60 ± 117.23	.258	.082	.345

NA, not applicable.
*Diagnostic central compartment.
†Foreign body removal central compartment.
‡Foreign body removal peripheral compartment.
§Statistically significant.

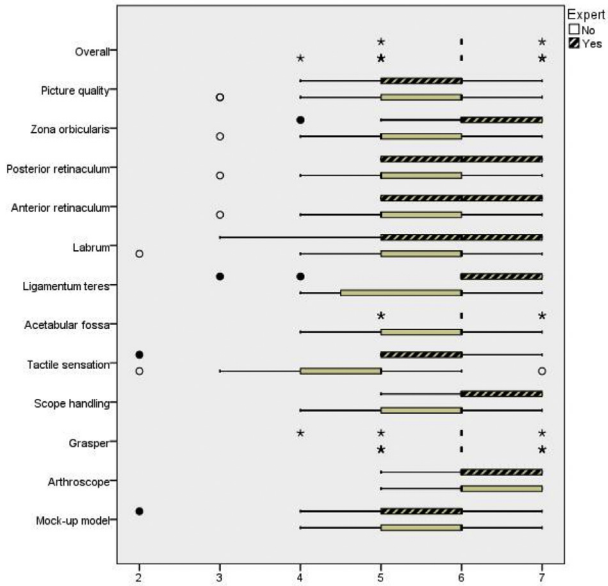

Fig 4. Summary of face validity grouped by experience level. Solid horizontal black lines indicate medians, bottom of the boxes represent the 25th percentile, top of the boxes represents the 75th percentile, whiskers represent the range of the nonoutlier data, circles represent the outliers between 1.5 and 3 times the interquartile range, and asterisks represent the extreme outliers (more than 3 times the interquartile range).

correlation between the metric parameters and the global ASSET. These findings correspond to previously published data of metric parameters recorded by the tested simulator and the ASSET global rating scale.[8]

The simulator demonstrated good face validity evaluated by experts and nonexperts. Eighty percent of the participants graded the overall impression in terms of realism as "completely realistic" (7) or "close to realistic" (6). In accordance with previously published data, these results are considered satisfactory in terms of face validity.[8,18] Although newer high-fidelity virtual reality simulation devices continue to develop improved graphics to further enhance realism, the role of overall face validity itself as a contributing factor to skill transfer remains unclear. Although current literature supports the fact that haptic feedback, a subdomain of overall face validity, may play an important role in acquisition of advanced surgical skills, it is the author's opinion that face validity is essential for broad acceptance of the technology as a teaching tool.[19] However, realism of haptic feedback of the tested simulator was graded as less favorable: "completely realistic" (7) or "close to realistic" (6) by only 18% of nonexperts and 56% of experts, respectively. The fact that experts generally rated haptic feedback of the device as more favorable compared with nonexperts might be explained by the nonexperts' lack of hands-on experience in hip arthroscopy.

Overall, the findings of the questionnaire are supported by previous studies reporting results of construct and face validity of the ArthroS simulator for training of knee and shoulder arthroscopy.[18,20]

The majority of arthroscopy simulators based on dry- or 3-dimensional models do not provide the trainee with the possibility to practice the placement of arthroscopy portals. As a result of the large soft tissue envelope and the tight ball-and-socket configuration of the hip joint, establishing the correct portals without endangering structures within the portal trajectory is particularly critical. This simulator provides the possibility to exchange the standard inlay with predefined portals for penetrable memory foam. It is then possible to probe the foam and confirm correct portal placement via a simulated image intensifier. Although face validity of the portal placement functionality was graded as "useful" (6) to "somewhat useful" (5) by 8 experts, again its transfer validity remains unclear. Although key features including palpable superficial anatomic structures and loss of resistance when entering the joint capsule are recreated by the simulator, the material property of the foam differs widely from human soft tissue.

Limitations

The Likert-scale–style questionnaire is subjective and therefore prone to systematic error. However, we chose this type of scale because it has reliably been used in the past and was shown to be a valid tool.[8,18]

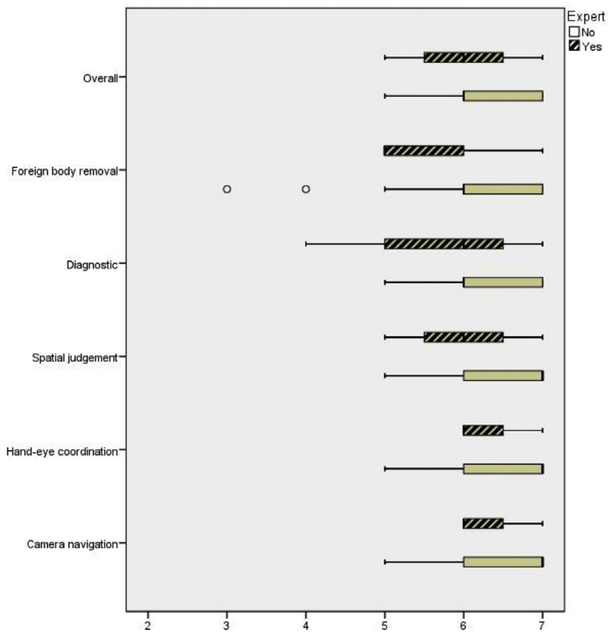

Fig 5. Summary of training utility grouped by experience level. Solid horizontal black lines indicate medians, bottom of the boxes represent the 25th percentile, top of the boxes represents the 75th percentile, whiskers represent the range of the nonoutlier data, circles represent the outliers between 1.5 and 3 times the interquartile range, and asterisks represent the extreme outliers (more than 3 times the interquartile range).

Furthermore, a significant difference of grasper path length in task 3 could not be demonstrated as a resulted of the small sample size and limited statistical power for this task. Otherwise, the power analysis performed a priori underestimated the expected difference in performance between the expert and nonexpert groups. Thus a smaller sample size than estimated a priori was sufficient to demonstrate significant differences. Also, even though none of the participants in the nonexpert group had previous experience in hip arthroscopy, the group consisted of board-certified orthopedic surgeons and residents with varying degrees of experience in knee-and-shoulder arthroscopy, possibly introducing bias.

Despite the high cost of purchasing and maintaining a simulator for orthopedic procedures, as well as its limitations in terms of haptic feedback, simulation is proven to be a safe way to acquire surgical skills and transfer them to the operating room.[21-24] However, the presented results do not allow us to draw any conclusion regarding whether skills acquired using the simulator transfer to the operating room or whether training using the simulator leads to increased hip arthroscopy performance. As a result of its thick tissue coverage and the risk of injury to adjacent structures,[14] adequate portal placement, a crucial step in successfully performing arthroscopic procedures of the hip, can be particularly challenging. In this study, no objective measure of correct portal placement was recorded, and face validity assessed by hip arthroscopy experts was graded as less favorable for this task.

Conclusions

The tested simulator demonstrated high construct and face validity.

References

1. Colvin AC, Harrast J, Harner C. Trends in hip arthroscopy. *J Bone Joint Surg Am* 2012;94:e23.
2. Bozic KJ, Chan V, Valone FH III, Feeley BT, Vail TP. Trends in hip arthroscopy utilization in the United States. *J Arthroplasty* 2013;28:140-143.
3. McCarthy JC, Lee JA. Hip arthroscopy: Indications, outcomes, and complications. *Instr Course Lect* 2006;55:301-308.
4. Kowalczuk M, Bhandari M, Farrokhyar F, et al. Complications following hip arthroscopy: A systematic review and meta-analysis. *Knee Surg Sports Traumatol Arthrosc* 2013;21:1669-1675.
5. Mehta N, Chamberlin P, Marx RG, et al. Defining the learning curve for hip arthroscopy: A threshold analysis of the volume-outcomes relationship. *Am J Sports Med* 2018;46:1284-1293.
6. Reider B. Trouble with the curve. *Am J Sports Med* 2018;46:1281-1283.
7. Erturan G, Alvand A, Judge A, Pollard TCB, Glyn-Jones S, Rees JL. Prior generic arthroscopic volume correlates with hip arthroscopic proficiency: A simulator study. *J Bone Joint Surg Am* 2018;100:e3.
8. Rahm S, Wieser K, Wicki I, Holenstein L, Fucentese SF, Gerber C. Performance of medical students on a virtual reality simulator for knee arthroscopy: An analysis of learning curves and predictors of performance. *BMC Surg* 2016;16:14.
9. Tay C, Khajuria A, Gupte C. Simulation training: a systematic review of simulation in arthroscopy and proposal of a new competency-based training framework. *Int J Surg* 2014;12:626-633.
10. Phillips L, Cheung JJ, Whelan DB, et al. Validation of a dry model for assessing the performance of arthroscopic hip labral repair. *Am J Sports Med* 2017;45:2125-2130.
11. Pollard TC, Khan T, Price AJ, Gill HS, Glyn-Jones S, Rees JL. Simulated hip arthroscopy skills: learning curves with the lateral and supine patient positions: A randomized trial. *J Bone Joint Surg Am* 2012;94:e68.
12. Khanduja V, Lawrence JE, Audenaert E. Testing the construct validity of a virtual reality hip arthroscopy simulator. *Arthroscopy* 2017;33:566-571.
13. Koehler RJ, Amsdell S, Arendt EA, et al. The Arthroscopic Surgical Skill Evaluation Tool (ASSET). *Am J Sports Med* 2013;41:1229-1237.
14. Byrd JW, Pappas JN, Pedley MJ. Hip arthroscopy: An anatomic study of portal placement and relationship to the extra-articular structures. *Arthroscopy* 1995;11:418-423.
15. Dienst M, Seil R, Kohn DM. Safe arthroscopic access to the central compartment of the hip. *Arthroscopy* 2005;21:1510-1514.
16. Van Nortwick SS, Lendvay TS, Jensen AR, Wright AS, Horvath KD, Kim S. Methodologies for establishing validity in surgical simulation studies. *Surgery* 2010;147:622-630.
17. Moorthy K, Munz Y, Sarker SK, Darzi A. Objective assessment of technical skills in surgery. *BMJ* 2003;327:1032-1037.
18. Fucentese SF, Rahm S, Wieser K, Spillmann J, Harders M, Koch PP. Evaluation of a virtual-reality-based simulator using passive haptic feedback for knee arthroscopy. *Knee Surg Sports Traumatol Arthrosc* 2015;23:1077-1085.
19. Panait L, Akkary E, Bell RL, Roberts KE, Dudrick SJ, Duffy AJ. The role of haptic feedback in laparoscopic simulation training. *J Surg Res* 2009;156:312-316.
20. Garfjeld Roberts P, Guyver P, Baldwin M, et al. Validation of the updated ArthroS simulator: Face and construct validity of a passive haptic virtual reality simulator with novel performance metrics. *Knee Surg Sports Traumatol Arthrosc* 2017;25:616-625.
21. Cannon WD, Garrett WE Jr, Hunter RE, et al. Improving residency training in arthroscopic knee surgery with use of a virtual-reality simulator: A randomized blinded study. *J Bone Joint Surg Am* 2014;96:1798-1806.
22. Howells NR, Gill HS, Carr AJ, Price AJ, Rees JL. Transferring simulated arthroscopic skills to the operating theatre: A randomised blinded study. *J Bone Joint Surg Br* 2008;90:494-499.
23. Rehman S, Raza SJ, Stegemann AP, et al. Simulation-based robot-assisted surgical training: A health economic evaluation. *Int J Surg* 2013;11:841-846.
24. Aggarwal R, Ward J, Balasundaram I, Sains P, Athanasiou T, Darzi A. Proving the effectiveness of virtual reality simulation for training in laparoscopic surgery. *Ann Surg* 2007;246:771-779.